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Sipos resistors doped by ion implantation.

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SIPOS RESISTORS DOPED BY ION IMPLANTATION

by

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Professor in Charge

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TABLE OF CONTENTS

IX. LIST OF TABLES

X. LIST OF FIGURES

ABSTRACT

SIPOS (Semi-Insulating Polycrystalline Oxygen Doped Silicon) is a semi-insulating material with resistivity in the range of 10^6-10^{14} Ω-cm at room temperature. SIPOS films have been generally used to provide high voltage discrete and integrated devices. By heavily doping the film with phosphorus during chemical vapor deposition, these films can be made moderately conductive. Vertical ballast resistors have been fabricated successfully with this technique and material. The motivation of the present investigation is to study SIPOS films doped by ion implantation, and to assess their potential to provide high value per square resistors adaptable to bipolar linear integrated circuits.

Linear circuit applications occasionally require resistance in the 1MΩ to 50MΩ range. Since standard diffused resistors typically don't exceed 1000-2000 Ω/□, resistors of this magnitude would require an exorbitant amount of silicon chip area. This need for high sheet resistance prompted an investigation of doped SIPOS to supply sheet resistance in the 5KΩ/□ to 500KΩ/□ range. The combination of LPCVD (Low Pressure Chemical Vapor Deposition) film deposition and ion implantation of the resulting film was undertaken to see if doped SIPOS would provide an easily manufacturable material with sufficient control to routinely produce films in the above sheet resistance range.

A modification of a linear integrated circuit process has been designed and fabricated to provide an oxide isolated nondiffused resistor having high sheet resistance. The modified process utilizes boron or phosphorus doped SIPOS to provide sheet resistance in the 3.6KΩ/□ to 360KΩ/□ range. The process provides resistors which are linear to 2KV/cm. Between 2KV/cm and 6KV/cm, the resistance decreases by approximately 10%.

As measured by the four-point probe technique, sheet resistance of the impurity doped SIPOS films exhibited a critical sensitivity to ion implant dose similar to polysilicon. Actual resistance of the fabricated resistor differed somewhat from the four-point probe value for boron or phosphorus doped films. The difference in resistance is caused by the subsequent heat treatment and processing which are dissimilar for the four-point probe film and the completed resistor structure. SIPOS resistivity was found to be probe pressure sensitive. At the pressures typically used for four-point probe measurements, the sheet resistance was not affected. For 30KeV ion implant doses of $10^{14}/cm^2$ and less, the SIPOS structure did not show a linear behavior. Instead the structure exhibited a bimodal conduction resembling a diode under reverse bias.

I. INTRODUCTION

SIPOS is a semi-insulating polycrystalline silicon material doped with oxygen having a resistivity in the range of 10^6-10^{14} Ω-cm at room temperature. Aoki[1] et al studied the dependence of electrical resistivity of oxygen-doped films versus oxygen concentration and found that SIPOS resistivity increases as the atomic % of oxygen increases. SIPOS films have been used as high voltage insulators on discrete and integrated devices. Matsushita[2] et al used the SIPOS film and field-limiting rings as a replacement for the oxide passivation layer on planar devices to achieve npn and pnp transistors rated at 800V and 2500V. Mochizuki[3] et al utilized SIPOS on CMOS integrated circuit and did not need a channel-stopper diffusion required for the conventional oxide version, thus allowing higher packing density.

By doping the SIPOS film with phosphorus, Yamoto[4] et al fabricated vertical ballast resistors on transistors. The primary intent of this investigation is to study SIPOS resistors doped by ion-implantation and assess their potential for supplying high value per square resistors adaptable to integrated circuits. For bipolar linear integrated circuits, horizontal rather than vertical resistor structures are more desirable since one can design a wider range of resistance values with the horizontal structure.

Presently, bipolar linear integrated circuits utilize diffused and epitaxial regions of the process to provide resistors. Without adding any further processing steps, emitter, base, collector and pinch resistors are provided by the process and typically provide 5 Ω/□, 200 Ω/□, 1250 Ω/□ and 10K Ω/□.[5,6] Frequently it is desirable to have resistances which are larger than the 10K Ω/□ value supplied by the pinch resistor but not subject to the disadvantages of the current technology. Pinch resistors are very nonlinear, exhibit high leakage current and have a high temperature coefficient of resistance. Thus, a modified bipolar linear integrated circuit process was designed to investigate the potential of doped SIPOS to supply five times the sheet resistance of pinch resistors (50K Ω/□).

Since circuit applications occasionally demand resistance of 1MΩ to 50MΩ[7,8] a range of sheet resistance films around the 50KΩ/□ neighborhood was evaluated. The sheet resistance of SIPOS films was measured by the 4-point probe technique, and the resistance was characterized as a function of oxygen content and ion implant dose with a constant anneal condition of 1 hour at 900°C.

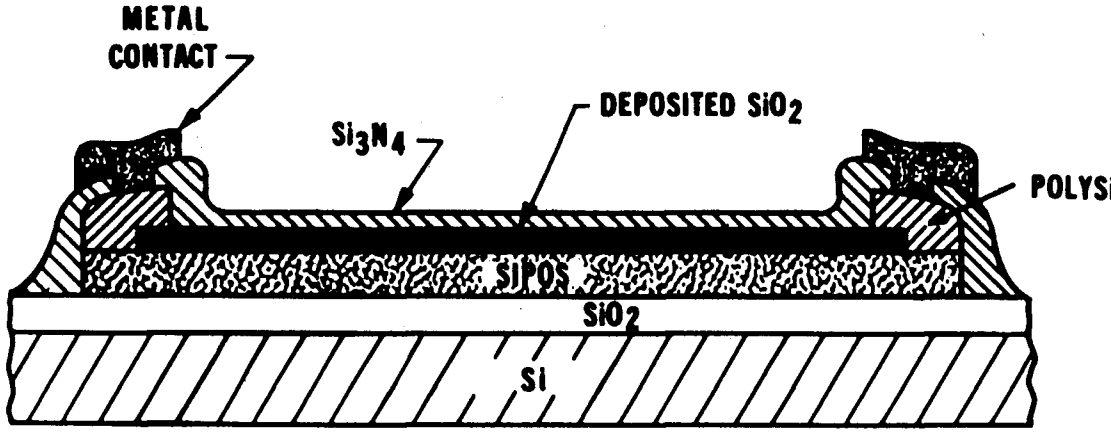
Ion implant doped SIPOS films were processed up to the polysilicon contact step at which time one can measure the sheet resistance of the film. Hence the films were characterized in terms of sheet resistance before any resistors were made.

Resistor test patterns were designed to study geometric effects on the resistance value as a function of the contact width, resistor

length, resistor width and resistor meander width. Next, a photolithographic mask set was fabricated to evaluate the resistor geometric effects and to determine various resistor characteristics. In particular, resistor reproducibility, contact resistance, linearity and temperature coefficient of resistance were measured.

Current integrated circuit processing technology utilizes plasma and chemical etching for pattern definition and both techniques were used in this study. In order to define the deposited oxide, the process employs a photoresist mask and chemical etching. The process employs both plasma etching with a photoresist mask and plasma etching with a deposited oxide mask to define the polysilicon contacts and the SIPOS resistor body, respectively. The process offers nondiffused crossovers which are available since polysilicon and a deposited oxide are added to the integrated circuit process.

Resistor structures were successfully fabricated and metalized as shown in Figure 1 with silicon nitride covering the resistor sidewall, thus sealing the resistor body. Two lots were processed and provided resistors in the 50KΩ/□ neighborhood. Contact resistance was found to be typically less than one square of sheet resistance and the temperature coefficient of resistance less than values obtained on pinch resistors. For low impurity doses, the SIPOS resistors exhibit a breakdown voltage, whereas at higher doses the resistors exhibit a nearly linear behavior. SIPOS and polysilicon similarities and dissimilarities are finally discussed.



SIPOS RESISTOR STRUCTURE

FIGURE 1

In essence a resistor replacement for pinch resistors and other high resistance applications has been designed, fabricated and electrically evaluated. The SIPOS resistor adds processing steps, but supplies numerous advantages. SIPOS resistor usefulness, resistor processing and sheet resistance of implant doped SIPOS are discussed in the first three sections. Resistor properties: contact resistance, temperature coefficient of resistance and resistor linearity are discussed in Section 5. Finally, a discussion of the elementary physics of implanted SIPOS resistor structures and the layout of the resistor test pattern are both described in the last sections.

II. SIPOS RESISTOR USEFULNESS

Bipolar linear integrated circuits utilize the diffused and epitaxial regions of a wafer to provide resistors and crossunders. This is quite convenient since the emitter, base, collector and base under emitter regions of a wafer have typical sheet resistances of 5 Ω/□, 200 Ω/□, 1250 Ω/□ and 10K Ω/□.[5,6] Thus the emitter diffusion provides a low resistance crossunder and the base, collector and base under emitter diffused/epitaxial regions provide a range of resistance for resistors.

Occasionally circuit applications require 1MΩ to 50MΩ resistors which for a collector sheet resistance of 1250Ω/□ would require an exhorbitant amount of silicon chip area ($12x10^3$μm to $6x10^5$μm length for a 15μm wide resistor). For some applications, it is also desirable to have a high voltage per unit length of resistance. Pinch resistors provide 10K Ω/□ resistance; however, they are extremely nonlinear and in the case of the base under emitter pinch resistor will sustain only about six volts. A bulk pinch resistor will sustain up to nearly the collector base breakdown voltage but is also very nonlinear. Two other disadvantages of pinch resistors are that they have high temperature coefficients of resistance and that one cannot simply achieve voltage ratios by tapping off the geometric length of the resistor. The doped SIPOS resistor overcomes many of

these disadvantages and provides both high sheet resistance and crossovers for linear integrated circuits.

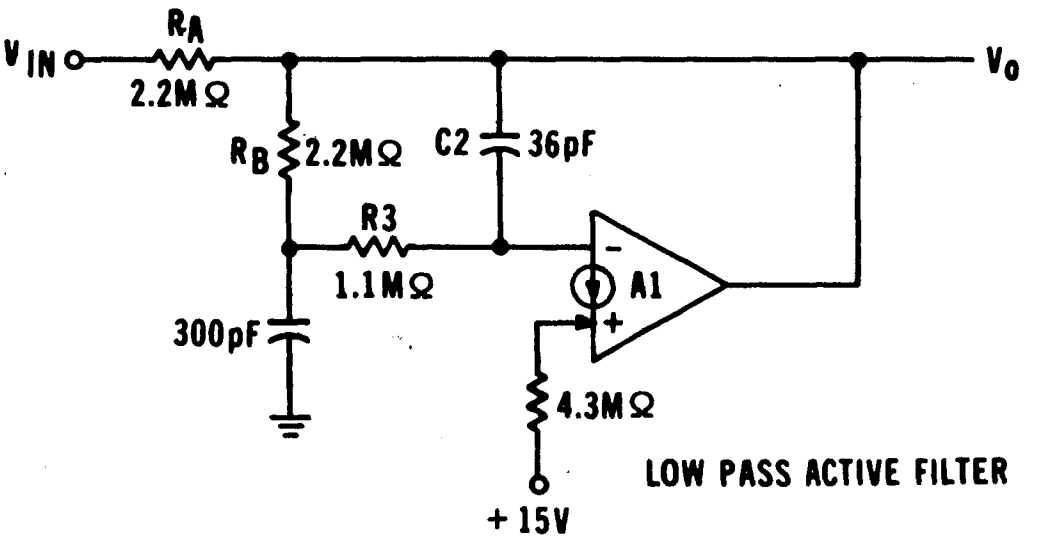
A. DOPED SIPOS OFFERS 50KΩ/□ SHEET RESISTANCE

A need exists for improved high value per square resistors on integrated circuits and recent work by Yamoto[4] et al indicates that phosphorus doped SIPOS offers this resistance, namely, 50KΩ/□. Yamoto's method of doping the SIPOS was to dope it during deposition. In this investigation, the dopant, phosphorus or boron, was introduced into the material by ion implantation. Ion implantation was selected since controlled depths and doses can be achieved in SIPOS. SIPOS thickness variations would not affect the depth of the conducting portion of the film (only the annealing would affect the depth for a given film), thus minimizing a critical variable. A second reason for selecting ion implantation is that it provides more uniform distribution of the dopant in both the grain and grain boundary area of a film than would be provided by diffusion.

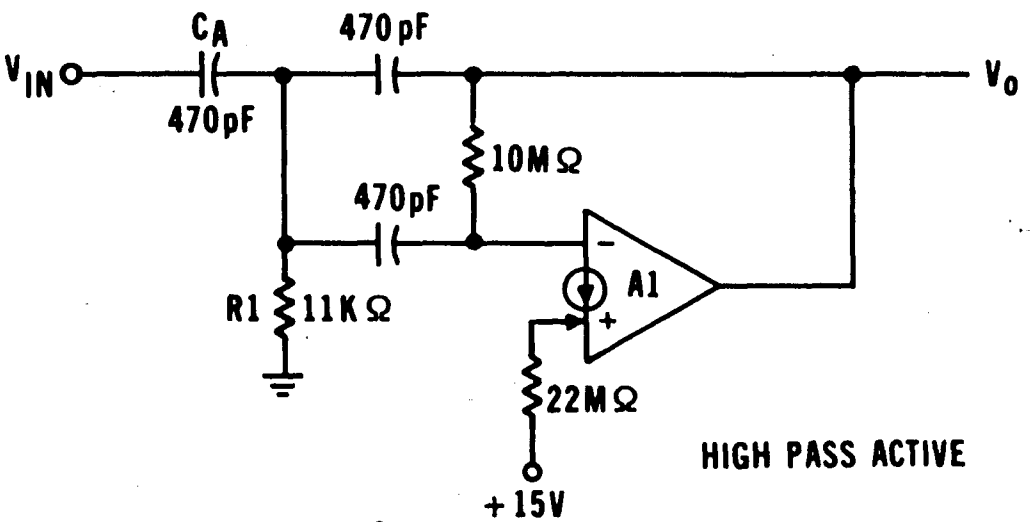
B. DOPED SIPOS RESISTOR PROCESS DESIGN OFFERS ADDITIONAL BENEFITS

The structural design of the doped SIPOS resistor provides numerous benefits. Comparing the doped SIPOS resistor to the diffused resistor, the SIPOS resistors have no junction leakage as is experienced by the standard diffused resistors; diffused resistors experience the saturation current of the reverse biased p-n junction surrounding the resistor. Another benefit provided by implant doped SIPOS is resistors capable of sustaining high voltages as well as

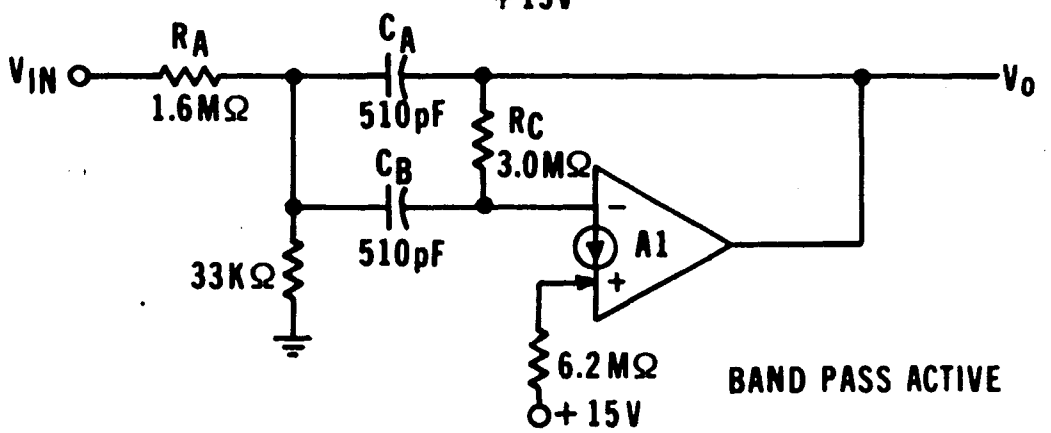
high voltages per unit length. The SIPOS resistors can sustain electric fields of 7KV/cm and higher before burning out. The resistors are linear up to electric fields of 2KV/cm and nearly linear up to 6KV/cm. Preliminary results indicate that the temperature coefficient of resistance is much better than that of pinch resistors and is in the neighborhood of the value of the diffused resistors. SIPOS resistors might be useful in low pass, high pass and bandpass active filters in a hybrid integrated circuit as shown in Figure 2[7] where the large capacitors would be supplied by using a very high quality (low defect density) deposited oxide. However, a 5000Å layer of SiO_2 would require approximately a 1500μm by 1500μm square area to produce a 470 pF capacitor, requiring a large amount of silicon chip area. SIPOS resistors may also help provide distributed RC networks for electrical filtering. Some electrical filters were designed in the test pattern; however, they were not processed due to a time limitation. Lastly, the polysilicon contact which is highly doped provides resistive crossovers; hence, both high resistance per square and crossunder limitations of linear integrated circuit processes are overcome.



LOW PASS ACTIVE FILTER



HIGH PASS ACTIVE



BAND PASS ACTIVE

ACTIVE FILTERS

FIGURE 2

III. RESISTOR PROCESSING

The steps of the high value per square resistor process are listed in Table 1 and result in the structure shown in Figure 1. The process is pictorially outlined in Figure 3 and sandwiched between the emitter and contact window steps of an integrated circuit process. It requires two additional photoresist steps to an integrated circuit process, one to define a deposited oxide over the resistor body and the second to define a polysilicon contact pad to the SIPOS resistor itself.

A. SIPOS PROCESS

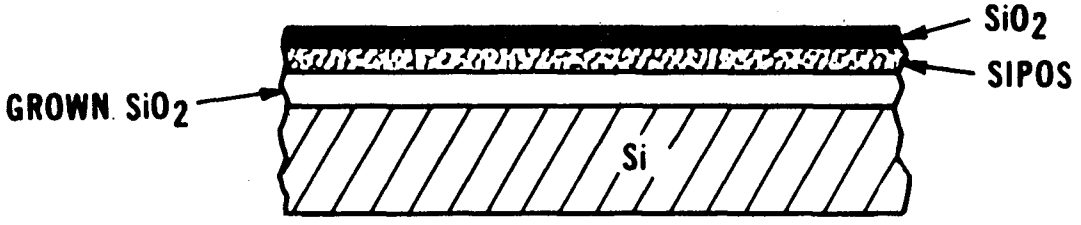
Prior to the SIPOS resistive film deposition, a 1050°C thermal oxide was grown of 6000Å thickness. Next 2300Å-4550Å of 644°C SIPOS was deposited in a Low Pressure Chemical Vapor Deposition (LPCVD) system which uses nitrous oxide (N_2O), silane (SiH_4) and nitrogen (N_2) gases. The oxygen content of the SIPOS film is controlled by adjusting the flow rate ratio of N_2O to SiH_4.[1] Many details of the deposition system and characteristics of the film have been described by Knolle and Maxwell.[17,18] Following the deposition, the SIPOS film was impurity doped at an energy of 30keV with boron or phosphorus. This energy was selected to allow for the projected depth range plus three standard deviations for the case of boron into amorphous SiO_2. Boron has a deeper depth range than phosphorus due to its small size and that depth is approximately 1900Å.[8] Next a 5000Å layer of silicon dioxide was deposited over the SIPOS at 892°C. Both films

TABLE 1

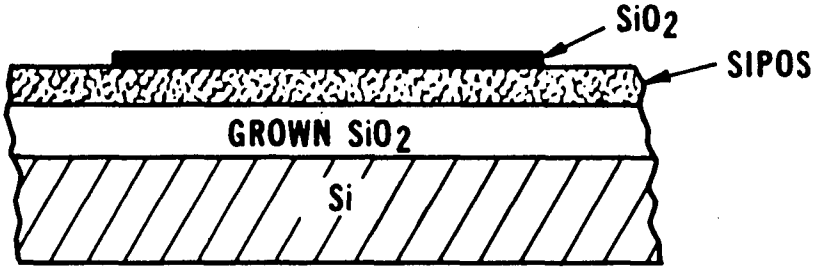
RESISTOR PROCESS

PHOTORESIST MASK LEVEL	PROCESS
	1. Grow 6000Å of SiO_2 at 1050°C
	2. Deposit ~3000Å of SIPOS (644°C)
	3. Ion Implant SIPOS (30 keV)
	4. Deposit ~5000Å of SiO_2 (892°C)
SIPOS Level	5. Photoresist SiO_2 and Chemically Etch Off Excess
	6. Deposit ~3000Å of Polysilicon (644°C)
	7. Ion Implant Polysilicon (30 keV) with $1.5 \times 10^{16}/cm^2$
Poly Level	8. Photoresist Polysilicon
	9. Plasma Etch Off Excess Polysilicon and SIPOS
	10. Subsequent Linear Integrated Circuit Processes

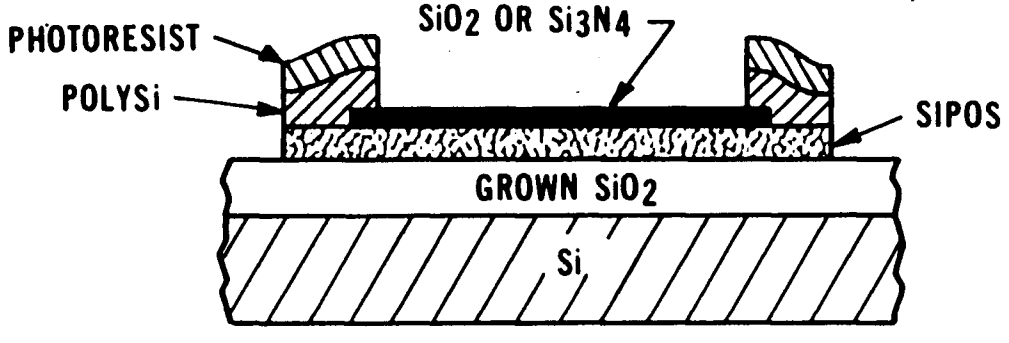
1. GROW SiO_2, DEPOSIT SIPOS, (IMPLANT), DEPOSIT SiO_2



2. PHOTORESIST AND ETCH SiO_2



3. DEPOSIT POLYSi, (IMPLANT), PHOTORESIST AND ETCH POLYSi AND ETCH SIPOS



4. STRIP RESIST

5. DEPOSIT NITRIDE

IMPLANTED SIPOS RESISTOR PROCESS

FIGURE 3

were deposited in a LPCVD system since this sytem offers better uniformity than the atmospheric CVD system. Note that the SIPOS film was partially annealed by the deposited oxide deposition process at this time.

At this point the oxide was covered with photoresist and etched. Unlike SiO_2 and Si_3N_4, SIPOS is virtually insoluble in buffered HF. This allows one to deposit an oxide over the top of the SIPOS and then to photolithographically pattern and etch the oxide without significantly affecting the SIPOS layer underneath.

After the deposited oxide is patterned and etched, 3000Å of polysilicon is deposited over the entire wafer and implanted at an energy of 30 keV and a dose of $1.5 \times 10^{16}/cm^2$. This film is next patterned into resistor contacts. A more desirable method of contacting the resistor is to dope the polysilicon in-situ. This would have eliminated the implant step and minimized contact resistance; however, doped polysilicon was unavailable at the time of the experiment. In the last part of the resistor process, the polysilicon is photoresisted and etched in a plasma reactor to remove the excess polysilicon and the excess SIPOS.

B. PLASMA ETCHING OF SIPOS RESISTOR

An IPC 2000 plasma reactor was used to etch the excess polysilicon and excess SIPOS. Initially, wafers were etched one at a time until the 1050°C thermal oxide color showed uniformly across the

wafer. This can be viewed through the see-through door of the plasma chamber.

The 1050°C thermal oxide was steam grown and has a much lower etch rate in the plasma than the deposited SIPOS or deposited oxide. Etch rates of the field oxide have been estimated to be one-tenth the rate of SIPOS in carbon tetrafluoride 14+4% oxygen gas. Prior to plasma etching, the slices were preheated to 100°C. Preheating speeds up the reaction, giving reasonable etch rates.

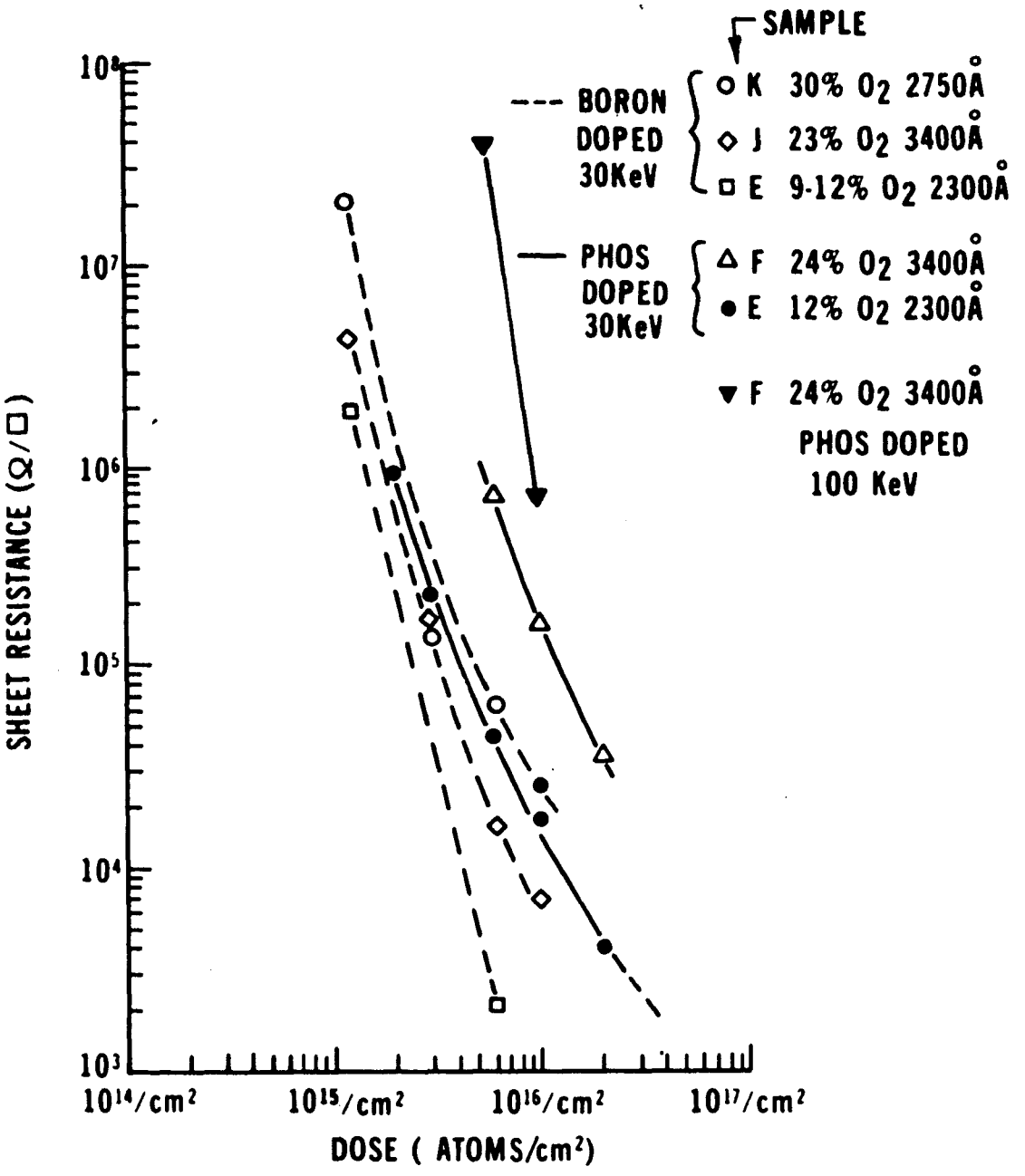
When wafers were etched one at a time, an etch rate of approximately 460Å/min. was obtained. If wafers were etched in quantities of approximately 10, the etch rate dropped to about 150Å/min. The leading wafers always etched more quickly, requiring sequential removal from the chamber; otherwise, severe undercutting of the material under the photoresist could occur on the leading wafer(s). Etch time varied by approximately 20-30% across a wafer.

IV. SHEET RESISTANCE OF IMPLANT DOPED SIPOS

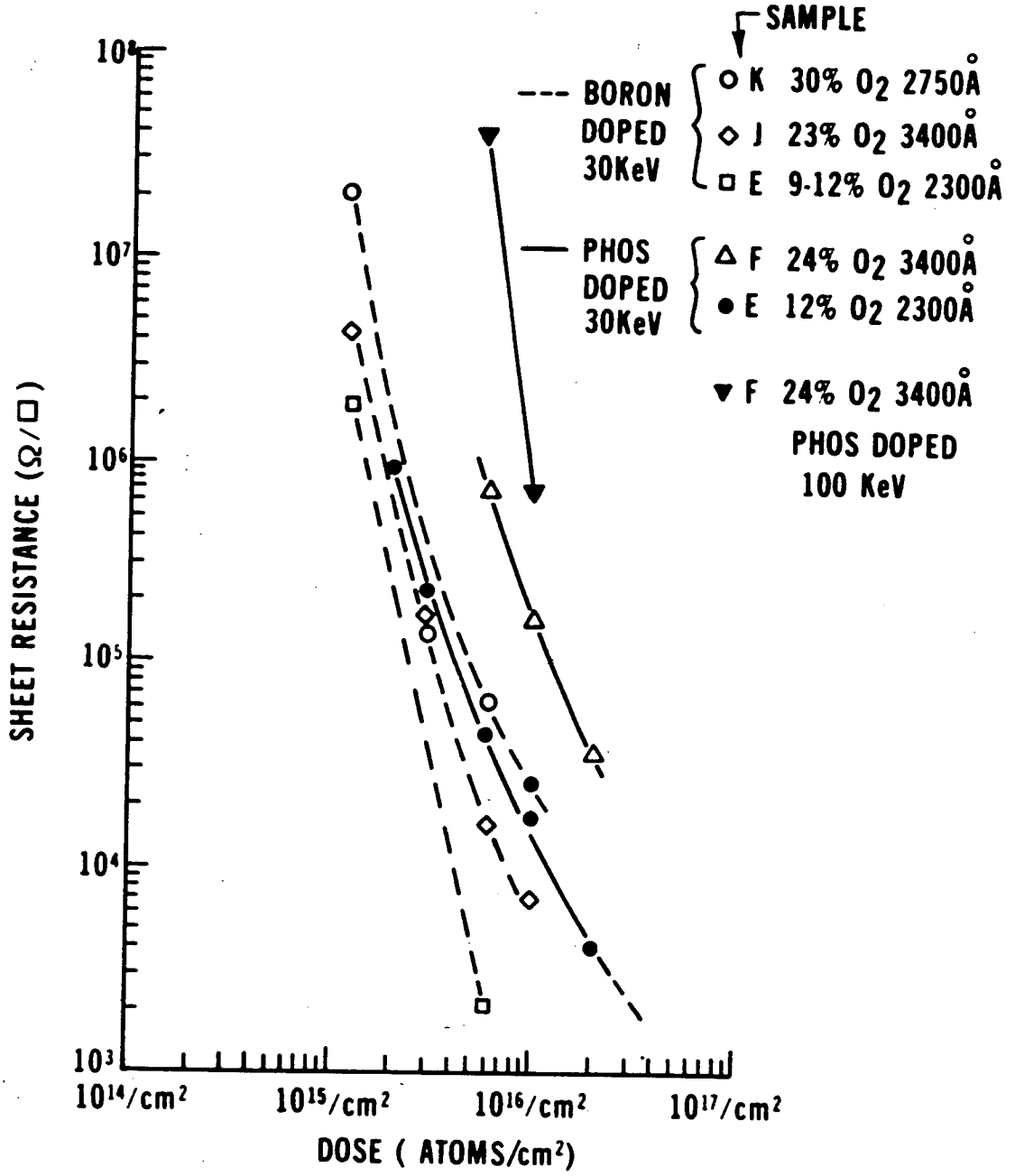
Figure 4 contains the measured sheet resistance dependence of SIPOS on impurity doping (boron and phosphorus) and the sheet resistance dependence of SIPOS on oxygen concentration. As the atomic percent of oxygen increases, the sheet resistance also increases for the range of implant doses shown in the figure. As the ion implant dose increases, the sheet resistance decreases.

The sheet resistance was measured using a four-point probe and fairly good agreement was achieved between the actual fabricated resistor and the four-point probe measurement for phosphorus doped films. For boron doped films, a significant difference exists between the four-point probe measurement and the actual fabricated resistors. These results are shown in Table 2. The resistance values of phosphorus doped resistors are about 25% below the values expected from four-point probe measurements. However, the boron doped resistors are as much as a factor of ten lower than the value expected from four-point probe measurements.

Figure 5 shows the four-point probe values after a one-hour 900°C anneal and the resistor values graphed alongside one another for the boron doped SIPOS. The difference exhibited between the two curves is caused by the subsequent heat treatments and processing which are dissimilar for the four-point probe film and the completed resistor structure. The completed resistor structure receives



SHEET RESISTANCE VS IMPLANT DOSE
FIGURE 4



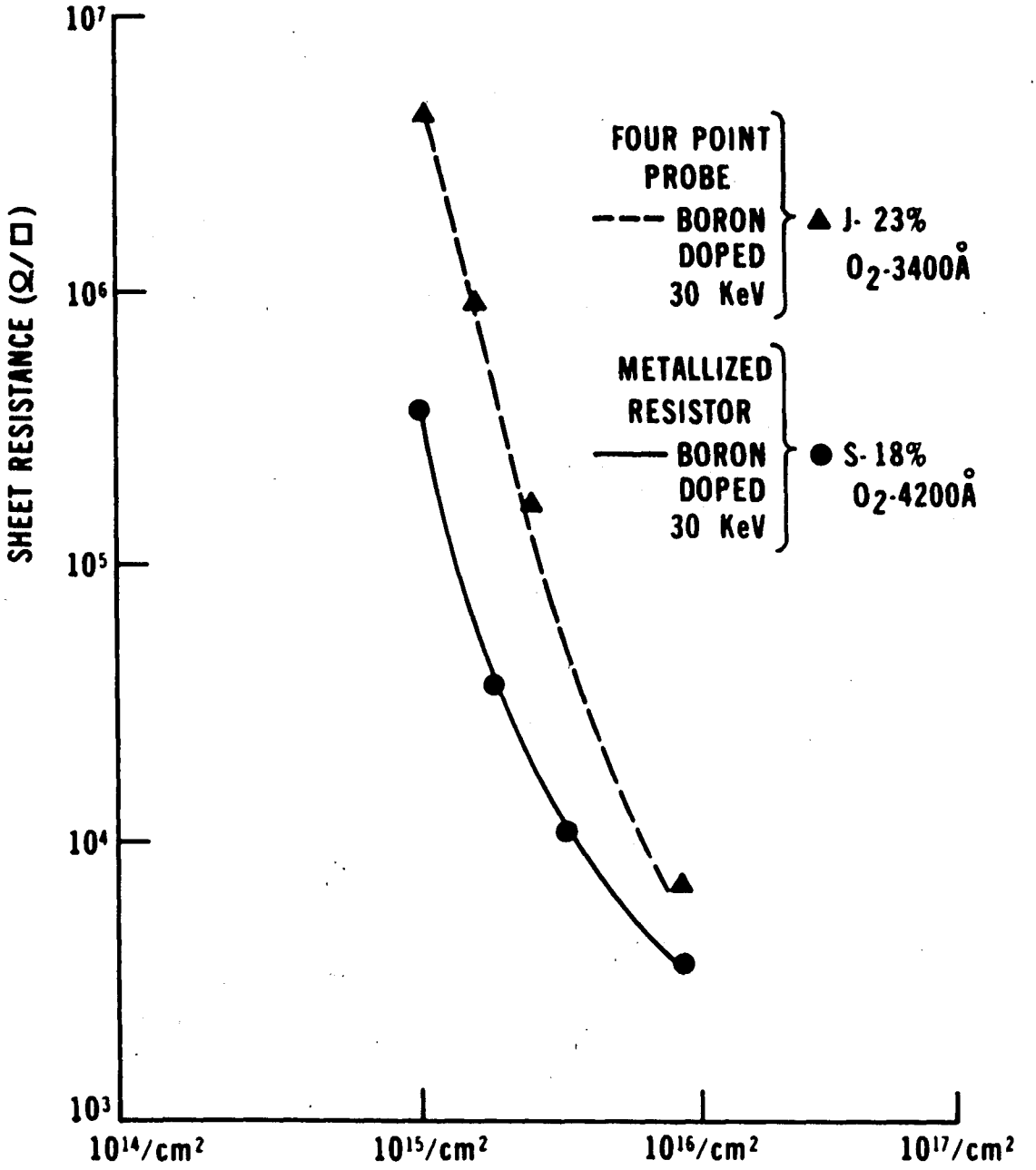
SHEET RESISTANCE VS IMPLANT DOSE
FIGURE 4

TABLE 2

SHEET RESISTANCE

SLICE NO.	DOPANT	FOUR-POINT PROBE*	METALIZED RESISTOR	DOSE/CM^2
R13	Phos.	62 KΩ/□	46.9 KΩ/□	$1.5x10^{16}$
R14	Phos.	62 KΩ/□	44.1 KΩ/□	$1.5x10^{16}$
R3	Boron	50 KΩ/□	11.7 KΩ/□	$4x10^{15}$
R5	Boron	50 KΩ/□	11.1 KΩ/□	$4x10^{15}$
S4	Boron	5 MΩ/□	360 KΩ/□	$1.2x10^{15}$
S14	Boron	500 KΩ/□	33.5 KΩ/□	$2.2x10^{15}$
S22	Boron	50 KΩ/□	10.4 KΩ/□	$4x10^{15}$
S34	Boron	5.6 KΩ/□	3.6 KΩ/□	$1x10^{16}$

*Films were annealed for 1 hour at 900°C in nitrogen.



RESISTANCE OF SIPOS FILM
FIGURE 5

approximately 90 minutes of high temperature processing after the deposited oxide step whereas the four-point probe film receives 60 minutes. Redistribution of the doping, doping activation, different phase compositions and different grain sizes of the film may occur causing this discrepancy. Also the difference in atomic % oxygen caused some of the change noted. Interestingly, as the doping is increased, the two curves in Figure 5 approach one another in terms of their electrical resistivity; this may be due to saturation of the doping activation. From the data in Table 2, one also notes that a $1x10^{16}/cm^2$ boron doped resistor is low by ~36% and a $1.5x10^{16}/cm^2$ phosphorus doped resistor is low by ~27%, hence suggesting the saturation of doping activation at higher dose concentrations.

The sheet resistance of implant doped SIPOS films is very critically sensitive to the implant dose and virtually no conduction (> $4x10^7$ Ω/□ sheet resistance) occurs for 3000Å thick films implanted at 30 KeV with doses less than $6x10^{14}/cm^2$ of boron. Also virtually no conduction (> $4x10^7$ Ω/□ sheet resistance) occurs for 30 KeV phosphorus implant doses of less than $1x10^{15}/cm^2$ as shown in Figure 4. The critical sensitivity of the sheet resistance to implant dose can be seen by looking at the boron doped 23% oxygen curve in Figure 5. The sheet resistance drops approximately two decades of resistance for one decade increase of implant dose for the boron doped annealed resistors. A very complex mechanism of impurity redistribution is probably occurring due to several known phenomena.

The SIPOS[18] film which consists of silicon, oxygen and impurity atoms is amorphous after deposition. During the heat treatments that follow SIPOS deposition, the film goes from an amorphous state into polycrystalline silicon and silicon oxide phases causing the physical thickness of the film to shrink by ~10%. As the heat treatment proceeds, crystallites (or grains) are formed each incorporating some of the impurity atoms with the remainder of the impurity atoms being incorporated between crystallites (in the grain boundary). At this point both grain and grain boundary diffusion occur. The diffusion coefficient for phosphorus in the SiO_2 species of the SIPOS film is much larger than the diffusion coefficient for boron. In the Si species of the SIPOS film a similar diffusion coefficient is obtained for both boron and phosphorus. In the grain boundary a different coefficient exists which is large for low temperatures. The segregation coefficient which gives a measure of the impurity redistribution at the silicon/silicon dioxide interface on crystallographic silicon is .3 and 10 for boron and phosphorus respectively. This provides some of the additional reasons for the different resistivities obtained for similar doses and depth of boron and phosphorus impurities.

A comparison of phosphorus doped SIPOS at 30 keV and 100 keV implant energies indicates that the sheet resistance is increased by using the higher energy as shown in Figure 4. Comparing boron doped SIPOS at 30 keV implant energy to phosphorus at 100 keV implant

energy, one notes that they both have similar depths into an SiO_2 or Si film (and thus SIPOS too) according to the projected range statistics. However, as shown in Figure 4, phosphorus doped SIPOS is more resistive for a given implant dose. Again these effects may be due to the complex diffusion in SIPOS and may depend on the anneal time and temperature.

From the first four SIPOS runs used to characterize the film, a mean of 23 atomic % oxygen was achieved with a standard deviation of ±3%. From Figure 4, a ±3% variation of oxygen content for the $4x10^{15}/cm^2$ boron dose gives approximately a 100% variation in the range of sheet resistance. The ion-implant dose which can be controlled to approximately ±3% gives about a 50% variation of the sheet resistance.

V. RESISTOR PROPERTIES

Several resistor properties were measured on both doped films and on metalized resistor structures. Contact resistance, temperature coefficient of resistance and resistor linearity with applied voltage were measured since they were considered to be most important.

A. CONTACT RESISTANCE OF SIPOS RESISTORS

Contact resistance of the SIPOS resistors can be calculated from the following formulas:

$$R = 2R_c + NR_{\square}$$

$$R_c = \frac{R - NR_{\square}}{2}$$

where

R_c = contact resistance (Ω)

N = number of squares ($\square$)

$R_{\square}$ = sheet resistance in ($\Omega/\square$)

R = resistance (Ω)

R is the measured resistance in the linear portion of the current-voltage trace. One can calculate both the contact resistance and the sheet resistance by measuring two resistors (R_1 and R_2) of different but known length (N_1 and N_2). Then one only needs to solve the simultaneous equations for R_c and R . Thus,

$$R_c = \frac{1}{2}\left(\frac{N_2R_1 - N_1R_2}{N_2 - N_1}\right) \quad ,$$

where R_1 and R_2 are the measured resistance values.

The contact resistance is dose and dopant dependent and provides a sheet resistance of .4 and .5 squares for phosphorus and .7 and .8 squares for boron for the doses shown in the following table. We can also see from the following table that the average contact resistance ($\overline{R_c}$) increases as the implant dose is decreased for a particular dopant.

DOPANT	SLICE	$\overline{R}_c$	SHEET RESISTANCE	IMPLANT DOSE/cm^2	$\overline{R}_c$/ SHEET RESISTANCE
Boron	R5	22.5KΩ	28KΩ	$4x10^{15}$	.8
Boron	R9	38.7KΩ	58KΩ	$3x10^{15}$	.7
Phosphorus	R14	27KΩ	61KΩ	$1.5x10^{16}$	.44
Phosphorus	R19	54.9KΩ	112KΩ	$1x10^{16}$	.49

B. TEMPERATURE COEFFICIENT OF RESISTANCE

Temperature coefficient of resistance (TCR) measurements were made on films of 12% oxygen concentration SIPOS doped with boron. These measurements were obtained by placing two probes approximately a centimeter apart onto the film and measuring the resistance while the slice was in an oven. Measurements were made with very light pressure gold wire probes to avoid contact pressure errors as shown in Figure 6. The $6x10^{15}/cm^2$ dose film gave a TCR of +705 ppm/°C.

SENSITIVITY OF SIPOS RESISTIVITY TO VARIOUS PROBE PRESSURES

FIGURE 6

Compared to diffused resistors, this is an excellent value. Diffused resistors typically have values of approximately 1800 ppm/°C and pinch resistors are even higher.

C. LINEARITY OF SIPOS RESISTORS

The linearity of SIPOS resistors is a function of the applied electric field and doping concentration. A study of six resistors, which are heavily doped ($1.5 \times 10^{16}/cm^2$ phosphorus), all having 75μm lengths and varying in width from 5μm to 30μm showed that the resistors are linear for electric fields $\leq$2KV/cm. For electric fields of 6KV/cm, the resistance decreases by 10% for 5μm resistor widths. However, for the 10μm to 30μm range of widths and at an electric field of 6KV/cm, the resistance decreases by about 5%. Further investigation revealed a processing anomaly which causes the resistor body near the contact end to widen on all resistors, but does not significantly affect the overall resistance except on narrow resistor widths (5μm). This accounts for the increase in resistance noted on the 5μm resistors and is described further in Section VII B.

Undoped SIPOS is virtually nonconductive (10^{10}-10^{18} Ω/□) at low electric fields. Lowly doped SIPOS exhibits a bimodal conduction behavior simulating that of a reverse breakdown characteristic of a diode. Both high and low doping concentration effects on the SIPOS resistors are described in the next section.

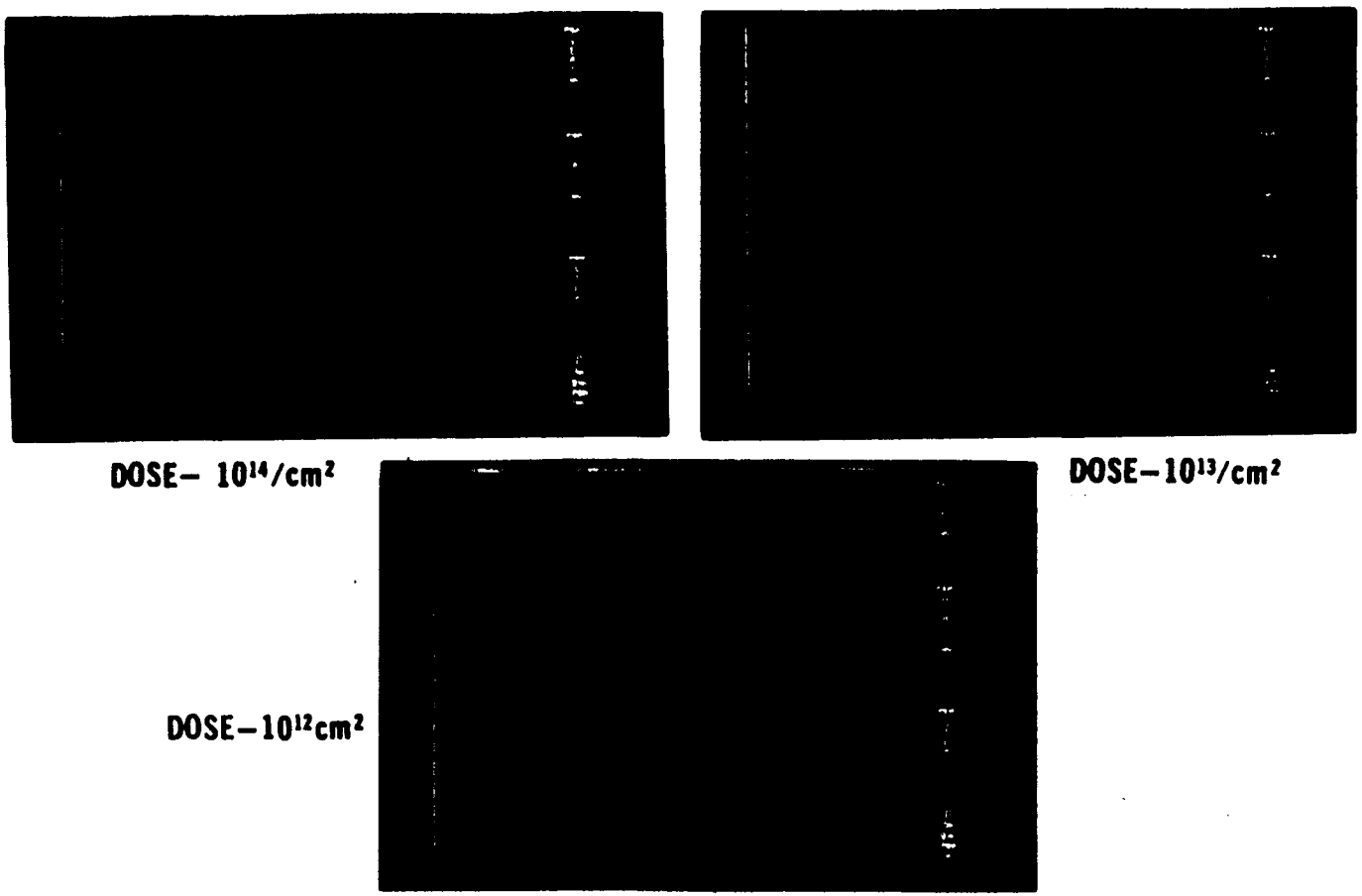
VI. ELEMENTARY PHYSICS OF IMPLANTED SIPOS RESISTOR STRUCTURES

Experimentally, SIPOS films implanted with doses of $10^{12}/cm^2$ to $10^{14}/cm^2$ exhibit a conduction behavior resembling that of a diode in reverse breakdown as mentioned in the previous section and as shown in Figure 7. Annealing for periods of one hour at 900°C or 1000°C does not affect the breakdown characteristic significantly. However, annealing at 1100°C causes the breakdown characteristic to soften. Doses between $10^{15}/cm^2$ to $10^{16}/cm^2$ exhibit nearly linear characteristics. Thus both conduction and breakdown mechanisms of electrical transport occur in impurity doped SIPOS films. For implant doses $\lesssim 10^{14}/cm^2$ ($\lesssim 3x10^{19}/cm^3$ concentration), a diode breakdown characteristic is observed. At some critical dose $\gtrsim 10^{14}/cm^2$ ($\gtrsim 3x10^{19}/cm^3$ concentration), linear conduction occurs as shown in the lower half of Figure 8 and is ohmic up to doses of $\sim 10^{16}/cm^2$. The above doses were implanted at an energy of 30 keV.

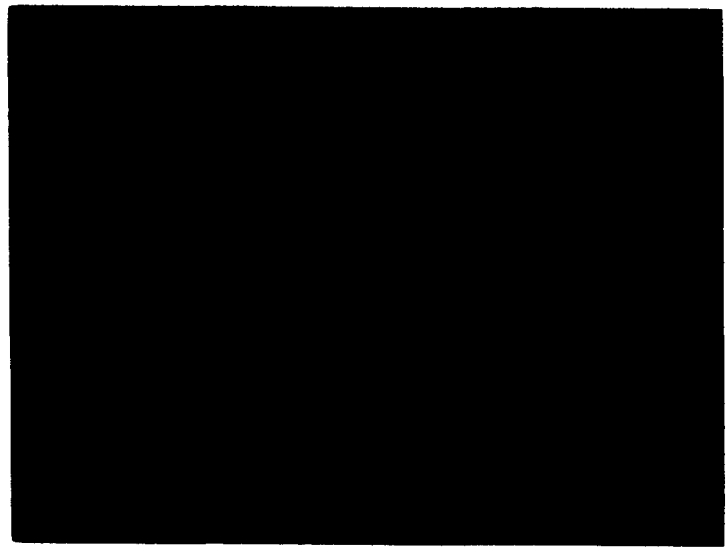
A. HIGH CONCENTRATION REGION

The high concentration region ($\gtrsim 3x10^{19}/cm^3$) provides nearly linear resistors as shown in the current-voltage characteristic of Figure 8 after the one-hour 900°C anneal of the polysilicon to SIPOS contact. Without an anneal the films exhibited a nonlinear behavior at the origin; the nonlinearity is suspected to be caused by an interfacial oxide and/or lack of doping activation.

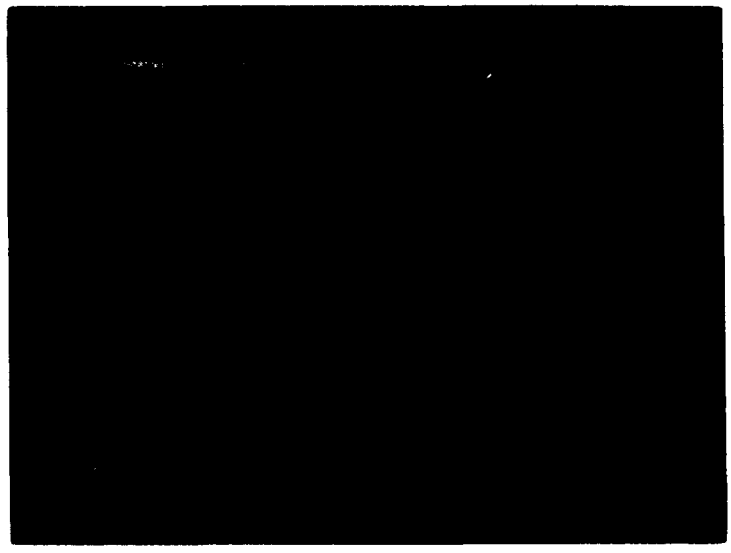
SIPOS is essentially an amorphous material as deposited. After annealing, grains begin to form in the material. Like polysilicon,



CURRENT-VOLTAGE SLOPE DEPENDENCE ON IMPLANT DOSE
FIGURE 7



BEFORE ANNEAL



AFTER ANNEAL FOR 1 HOUR
AT 900°C IN NITROGEN

LINEARITY OF A BORON DOPED 19% OXYGEN CONCENTRATION SIPOS RESISTOR

FIGURE 8

it can be treated physically as a network of crystallites doped with oxygen and boron or phosphorus. Thus it obeys polysilicon type conduction models.

A carrier-trapping model[9,10,11,12,13] has been used to explain the conduction behavior of doped polysilicon and this model appears to fit the conduction behavior noted in SIPOS. The model predicts grain boundary trapping states which trap part of the thermally ionized carriers. Hence the number of carriers is reduced and a potential barrier impeding carrier flow from crystallite to crystallite is generated. At high doping levels the potential barrier is easily tunneled through, causing the semiconducting action to be degenerate and allowing nearly ohmic behavior of the material.

B. LOW CONCENTRATION REGION

In the low concentration region ($\lesssim 3\times10^{19}/cm^3$), nearly 250 volts must be applied to a ~240μm long resistor (or an electric field of $\sim10^4$V/cm) before any conduction occurs. At this point, breakdown of the film occurs and the slope of the current-voltage trace in breakdown becomes nearly ohmic and dependent on the implant dose (see Figure 7).

According to the carrier-trapping model,[9,10,11,12,13] the potential barrier impeding carrier flow from crystallite to crystallite is not that of a degenerate semiconductor at these doping concentrations and must be overcome by approximately 1 volt/μm field before conduction occurs. Once this potential barrier is overcome,

then breakdown of the film occurs and the doping concentration in the grain determines the resistance of the current voltage characteristic shown in Figure 7.

C. POLYSILICON AND SIPOS SIMILARITIES AND DISSIMILARITIES

The conduction behavior of SIPOS and POLYSILICON appear to be similar in that polysilicon exhibits the critical dependence of the sheet resistance on implant dose as shown in Figure 9.[14] Polysilicon resistivity drops rapidly in the dose range of $10^{13}/cm^2$ to $10^{14}/cm^2$ while SIPOS requires doses in the $10^{15}/cm^2$ to $10^{16}/cm^2$ range before significant conductivity is obtained. Both polysilicon[15] and SIPOS can provide resistors of short lengths. See Figures 10 and 11. However, short length resistors (5μm to 20μm length) are susceptible to electrical burnout from voltage transients.

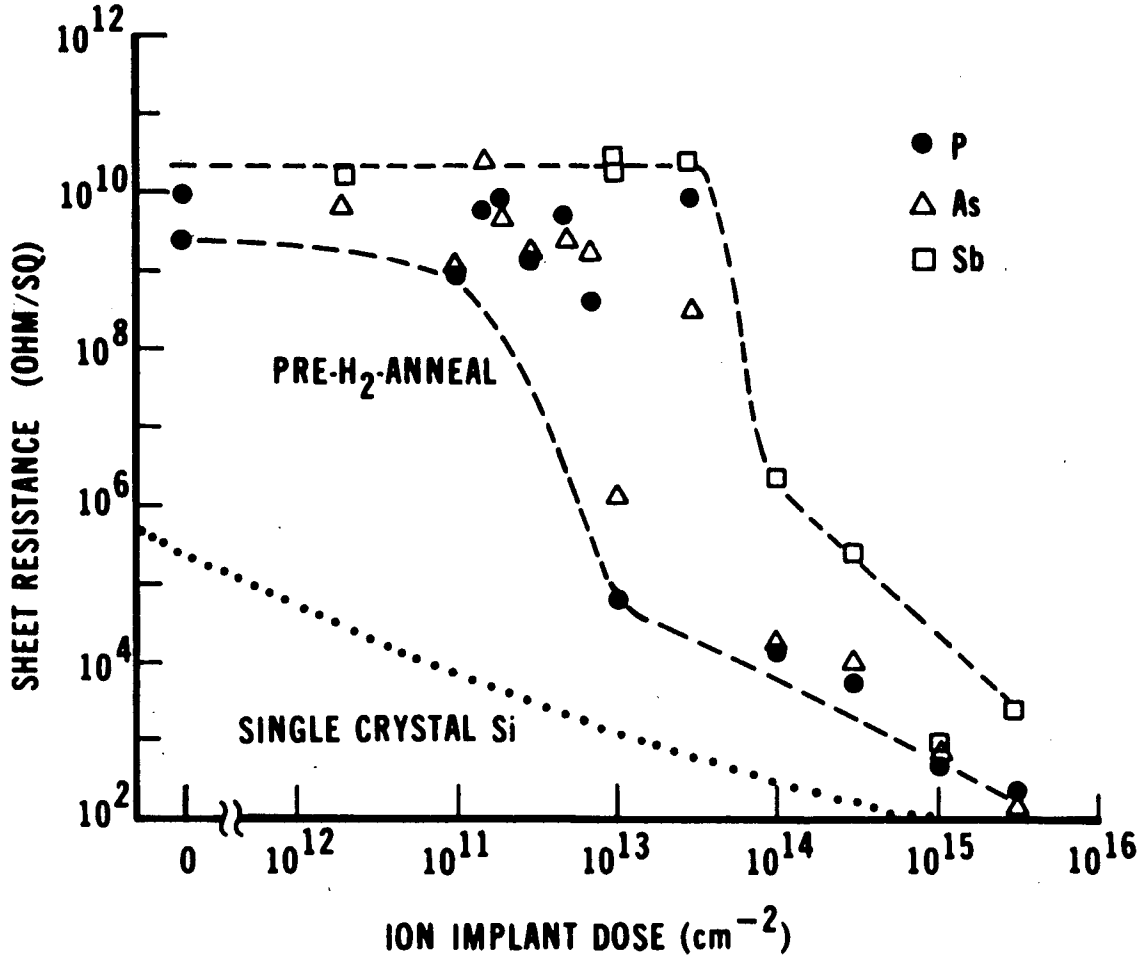
Gerzberg[9,16] studied the transport mechanism in polysilicon and concluded that the conduction of polysilicon is limited by the thermionic emission of majority carriers. He concluded that the current-voltage behavior of polysilicon obeys the following formula:

$$I = AJ = 2K \sinh \frac{q V_g}{2 kT}$$

A is area of the conduction portion of polysilicon film

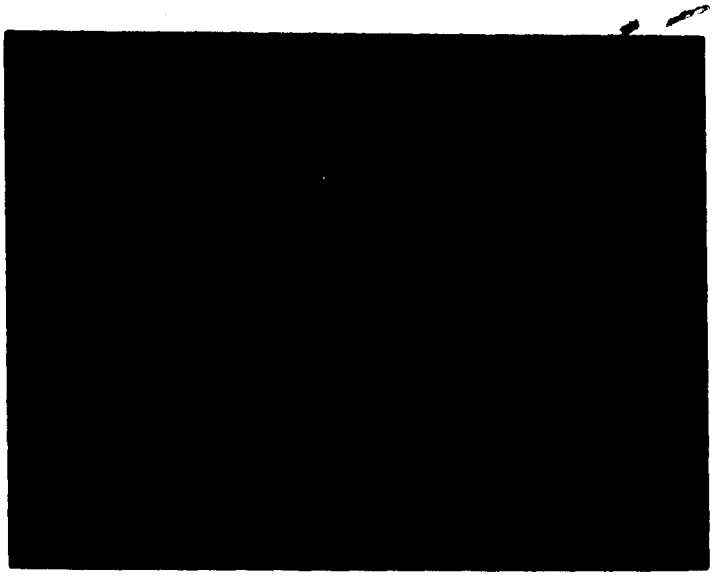
J is current density

V_g is voltage across a grain

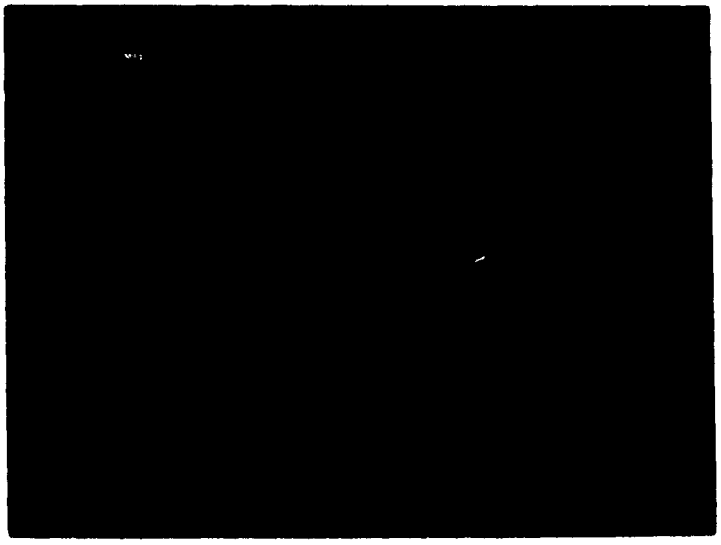


RESISTANCE OF IMPLANTED POLY-Si

FIGURE 9



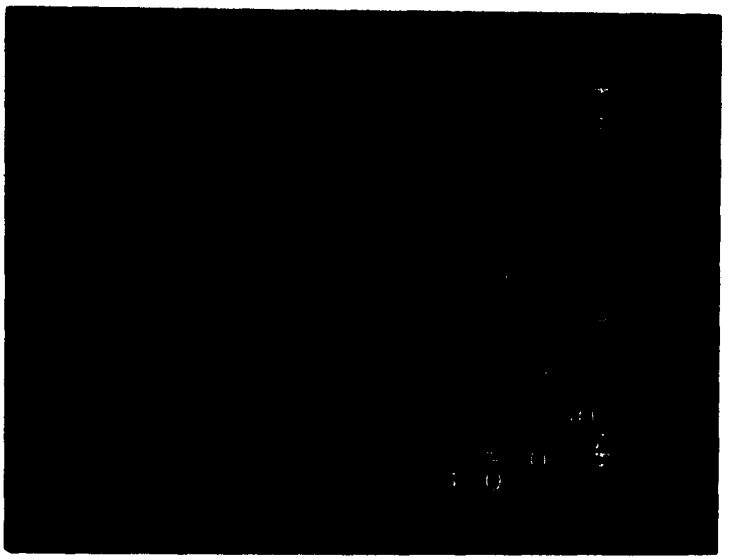
5μ LENGTH



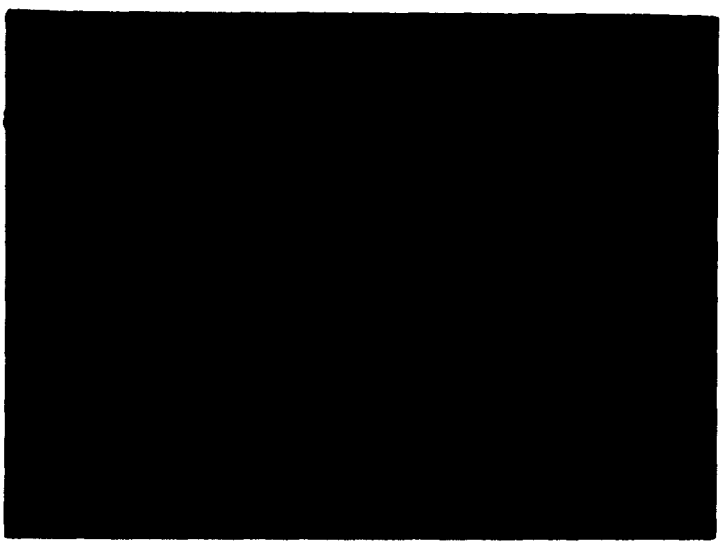
10μ LENGTH

POLYSILICON RESISTORS HAVING SHORT LENGTHS

FIGURE 10



"A" 20μ to 400μ LENGTH



"B" 5μ LENGTH

VARIOUS RESISTOR LENGTHS

FIGURE 11

$$K = AA^* T^2 \exp\left(\frac{-q V_B}{kT}\right)$$

A^* is the Richardson constant ($\approx 120 A/cm^2 \, °K^2$)

V_B is the potential barrier

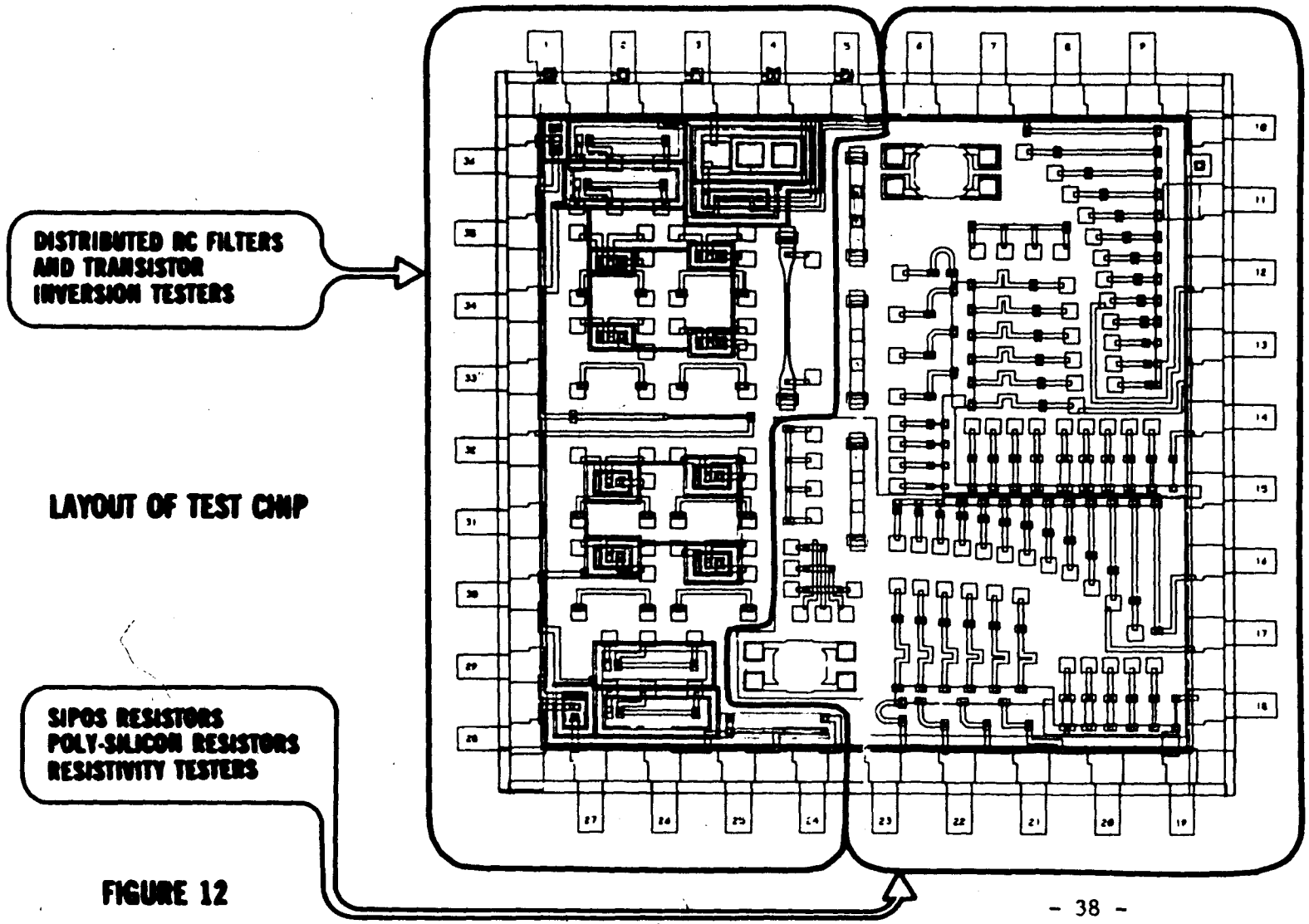
Figure 11A shows the I-V behavior for a family of SIPOS resistors ranging from 20μm to 400μm in length plus a single 5μm long resistor in Figure 11B. The nonlinearity due to high electric fields is apparent on the 5μm resistor and the magnitude of the electric field is indicated on the abscissa. The SIPOS resistance behavior for the high dose region looks like the hyperbolic sine function and appears to obey similar transport mechanisms as polysilicon.

VII. RESISTOR TEST PATTERN

A test pattern to study SIPOS resistors was developed and is shown in Figure 12. In general, the SIPOS resistor test pattern is laid out in two sections. One section is comprised of the SIPOS resistors, polysilicon resistors and the resistivity testers. The other section is comprised of the distributed RC electrical filters and transistor inversion testers. A list of the elements on the test pattern is given in Figure 13 and includes resistors, electrical filters, transistors and resistive crossovers. Varying lengths, widths, meanders and end contact size test resistors were fabricated and are detailed in Figures 14, 15, 16 and 17. Several low pass filters and one high pass filter were fabricated with the assumption that doped SIPOS could be represented as only a resistive component in the structures. Diffused regions supplied other resistive material; also, deposited and grown oxides supplied the dielectric for the distributed capacitance of the RC filters. In addition, several inversion test structures were fabricated to investigate the possibility of inversion effects over the diffused isolation areas of standard transistors. Due to a time limitation, only the SIPOS resistors were processed and examined in detail.

A. TEST PATTERN ELEMENTS

The topography of four sets of resistors is shown in Figures 14-17. The dashed area is the region that is metalized on the structure. In Figure 14, the size of the polysilicon connecting



LAYOUT OF TEST CHIP

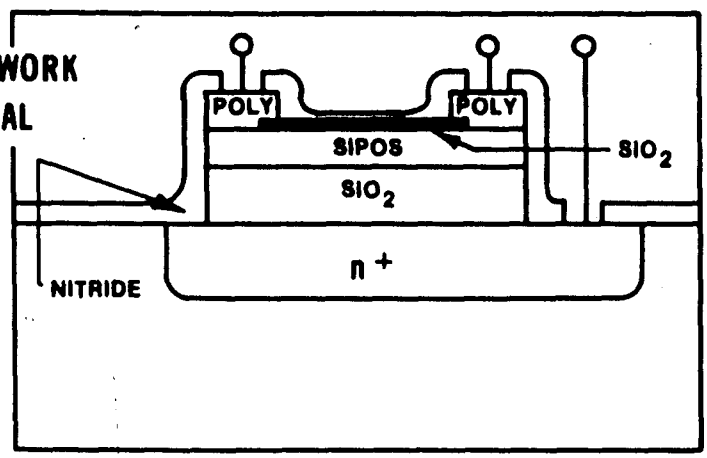
FIGURE 12

RESISTORS

1. VARIOUS LENGTHS OF RESISTORS WITH FIXED WIDTH
2. VARIOUS WIDTHS OF RESISTORS WITH FIXED LENGTH
3. VAN DER PAUW PATTERNS
4. MATCHED RESISTORS AND RATIOS OF RESISTORS
5. EXPERIMENTAL TYPES OF MEANDERS
6. EXPERIMENTAL RESISTOR END CONNECTIONS
7. EXPERIMENTAL BENDS

DISTRIBUTED RC NETWORK

THREE TERMINAL



TRANSISTORS

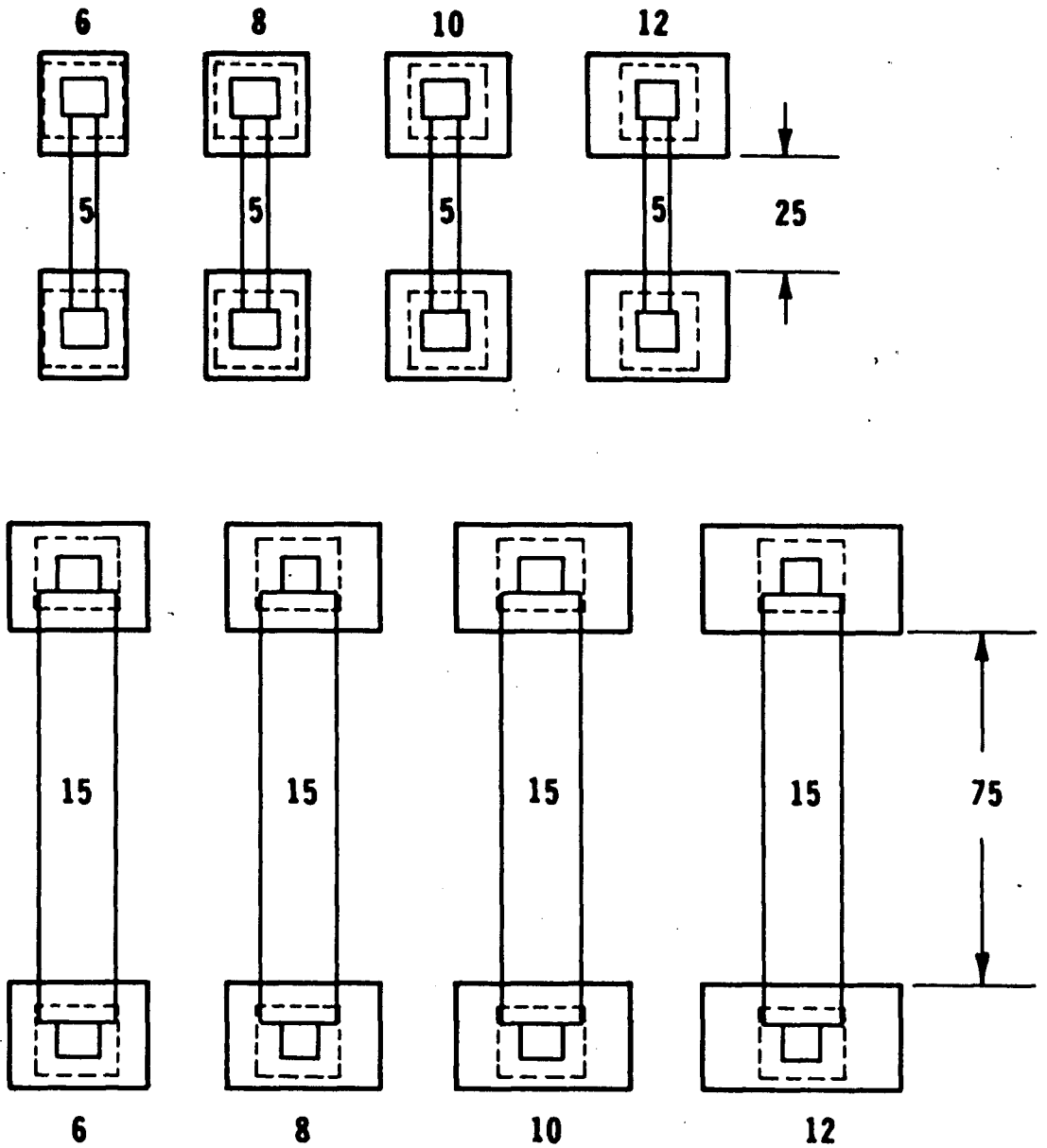
STANDARD NPN AND PNP

RESISTIVE CROSSOVER (WITH POLY Si)

SINGLE, DOUBLE, TRIPLE

ELEMENTS OF TEST PATTERN

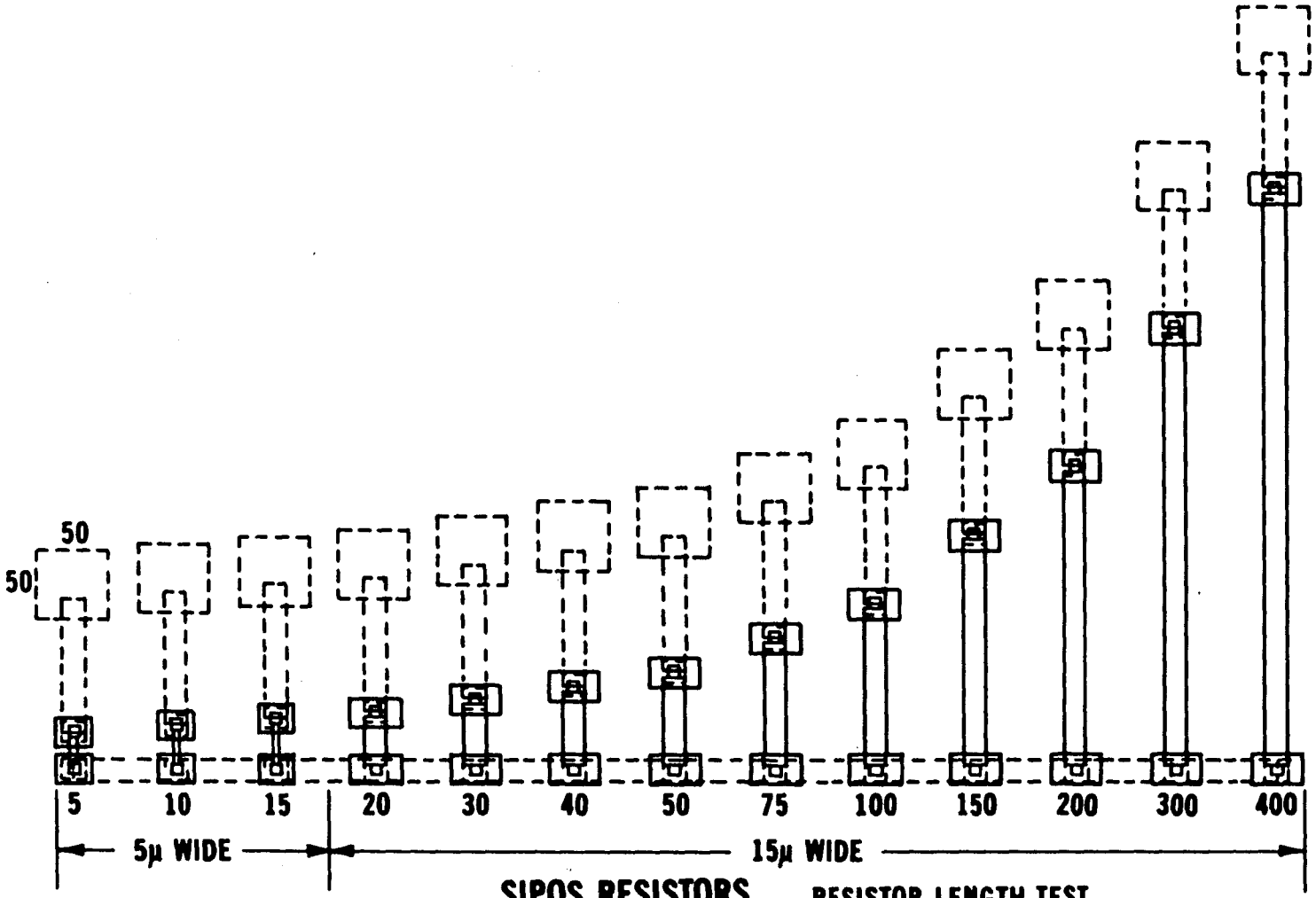
FIGURE 13



SIPOS RESISTORS

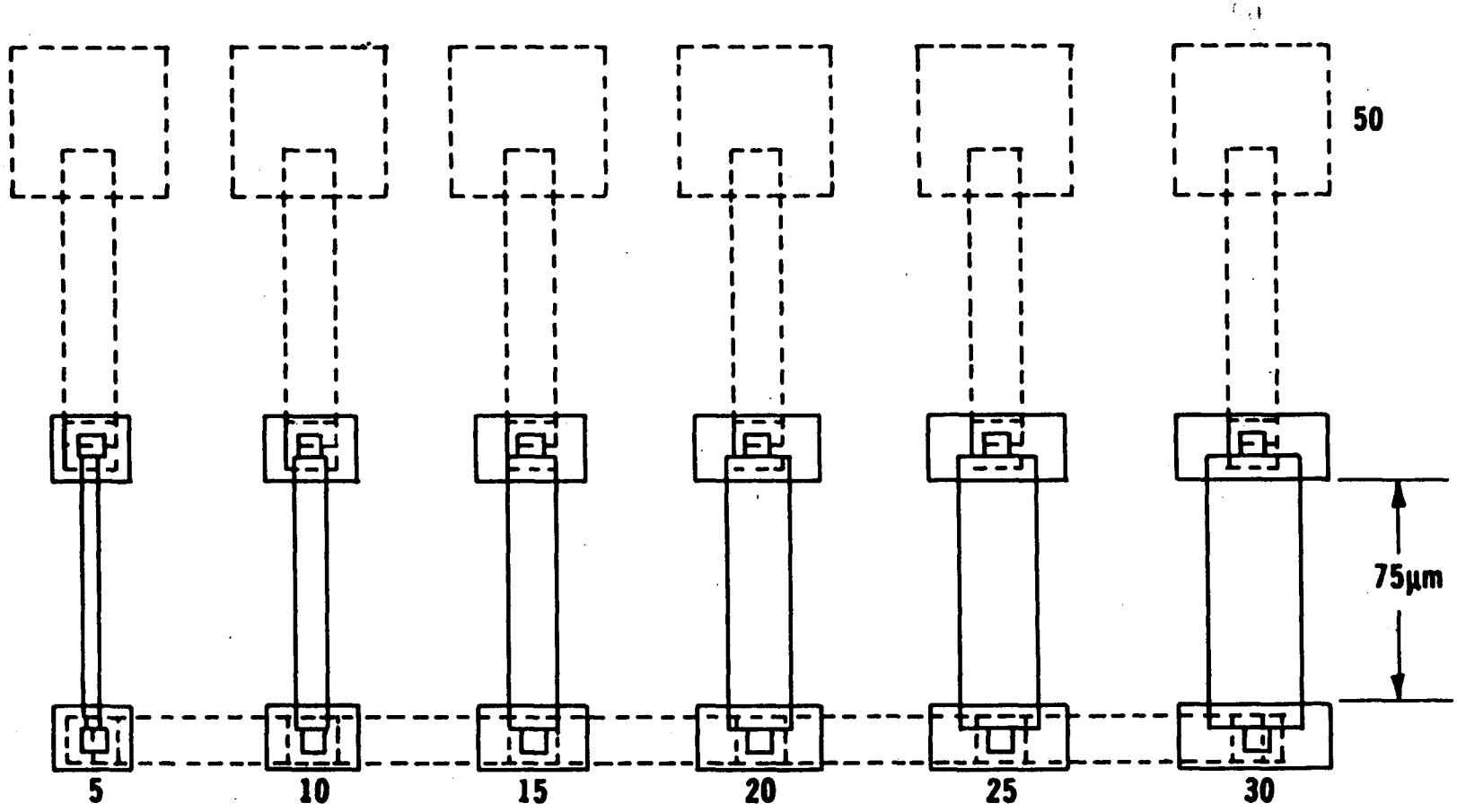
RESISTOR END CONTACT TEST

FIGURE 14

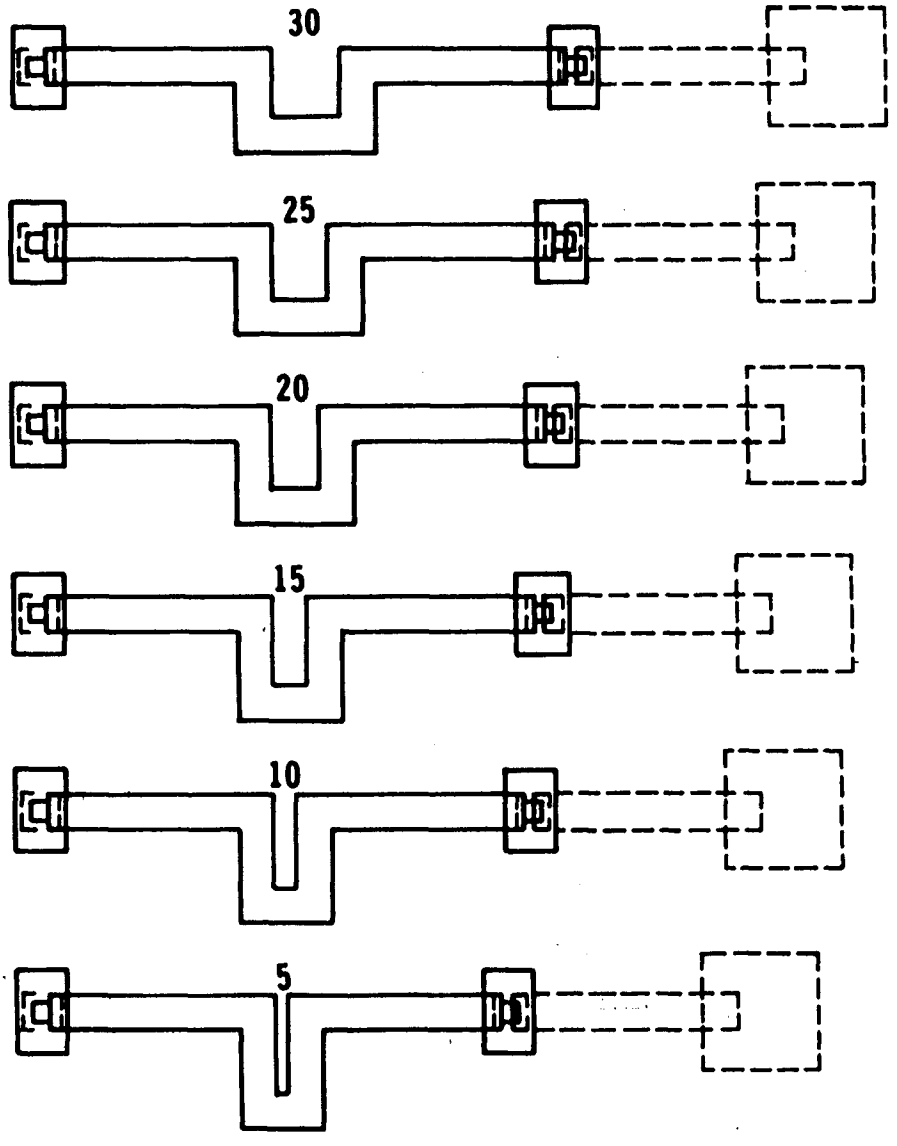


SIPOS RESISTORS RESISTOR LENGTH TEST

FIGURE 15



SIPOS RESISTORS
RESISTOR WIDTH TEST
FIGURE 16



SIPOS RESISTORS
RESISTOR MEANDER TEST

FIGURE 17

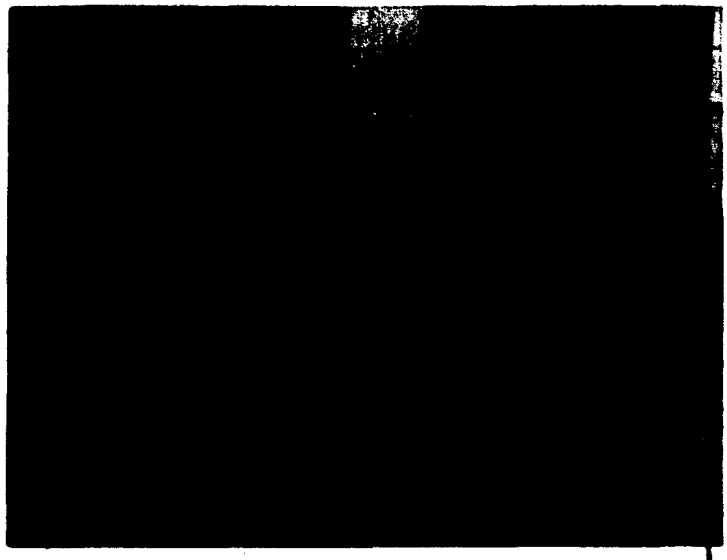
pad is varied for two different resistor widths (5μm and 15μm) to study contact resistance variation with connecting pad size. Figure 15 depicts resistor lengths from 5μm to 400μm with two different width variations: 5μm and 15μm. Figure 16 shows the variations of both the polysilicon connecting pad and the resistor width while Figure 17 shows the variations of the resistor meander but maintains the same number of squares of resistance.

Four distributed RC networks were fabricated on the test chip of the form shown in Figure 13. The SIPOS was made of a common length for the networks and the dielectric thickness underneath was varied by putting the SIPOS resistor over four oxidized areas of different thickness.

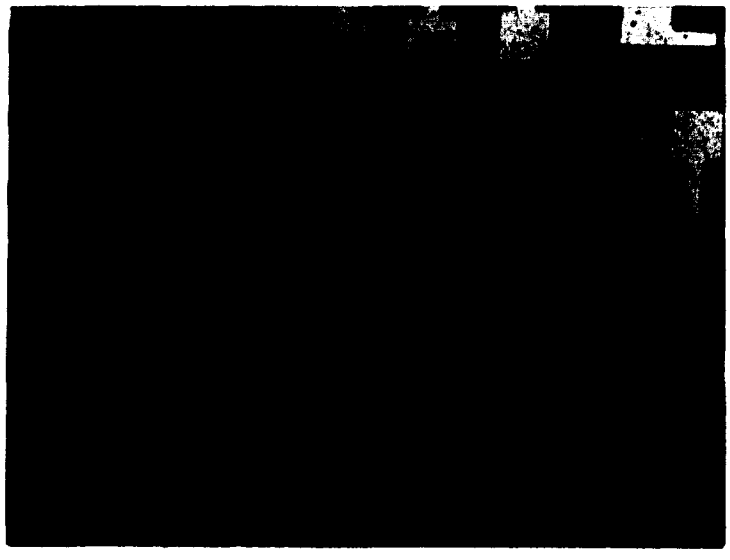
B. TEST PATTERN RESULTS

Devices were fabricated with resistors ranging from approximately 5KΩ to 10MΩ using the test chip showing in Figure 12. Both boron and phosphorus doped films were fabricated, although only boron resistors were made over the entire range indicated. Due to a time limitation, only the resistors and the resistive crossovers were fabricated; no RC filters and no transistor inversion structures were processed. The resistor end contact test showed that enlargement of the contact width by a factor of 2 lowered the resistance by only 2% for 5μm wide resistors. Enlargement of the contact width for the 15μm wide resistors showed no significant decrease in the resistance. From the resistor length test, the electric field dependence of

resistor linearity was discovered, as discussed earlier. The resistor width test showed that the calculated sheet resistance varies by 10% over the resistor width range of 5μm to 30μm. Over the resistor width range of 10μm to 30μm, the calculated sheet resistance varies by 5%. Since the resistors are located all within several hundred microns of one another, the actual doping of the SIPOS film should be quite similar and one would expect the sheet resistance to be similar between the resistors. The discrepancy results from an underetching variation which causes the resistor width near the connecting pad to be wider than the main body and hence be noticeable in narrow resistors as shown in Figure 18. The resistor meander test had loops varying from 5μm to 30μm in width. The test results indicate that the same resistance was obtained for the 10μm to 30μm wide loops, but the 5μm wide loop resistor was low by 2.5% due to a processing anomaly in which the processed resistor body was rounded at the meander as shown in Figure 19.

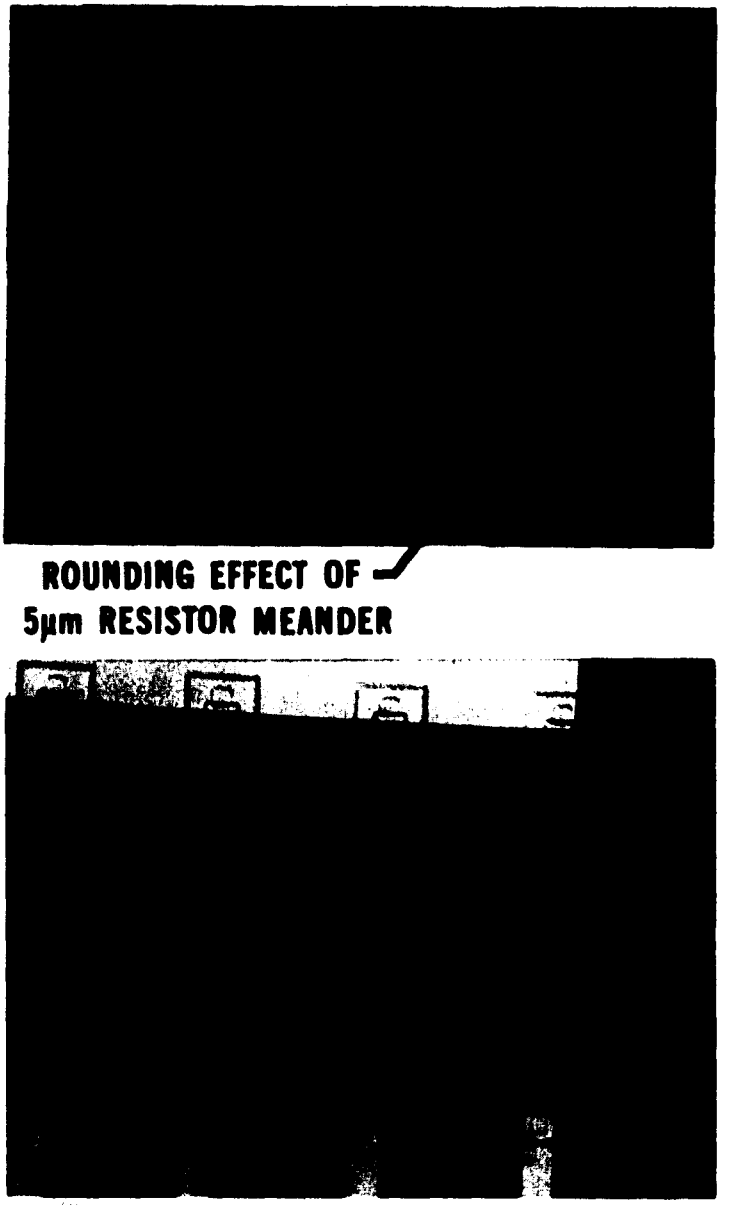


PROCESSING ANOMALY CAUSES WIDENING OF RESISTOR BODY NEAR CONTACT END



WIDENING EFFECT OF RESISTOR BODY NEAR CONTACT END

FIGURE 18



ROUNDING EFFECT OF RESISTOR MEANDER

FIGURE 19

VIII. CONCLUSIONS

A linear integrated circuit process has been modified to provide oxide isolated resistors having high sheet resistance, polysilicon crossovers and distributed RC electrical filters. This was accomplished by developing an addition to the process which utilizes two photoresist steps plus polysilicon, SIPOS and oxide depositions. The resistor body is composed of SIPOS doped by ion implantation and is contacted by two polysilicon pads. Sheet resistances in the range of 3.6KΩ/□ to 360KΩ/□ were obtained with the designed structure. Distributed RC electrical filters were designed to use SIPOS as a resistive-only component and to use the oxide under the SIPOS as the dielectric for the capacitance. The silicon and SIPOS formed the plates of the capacitor. The dielectric thickness was varied by depositing the SIPOS over thicker or thinner oxides of the silicon chip. Additional studies of the electrical filters and the polysilicon crossovers will supply information on their utility.

Test patterns were designed to study the geometric effects of processing on the final resistor. The resistor end contact tester showed that enlargement of the end contact width by a factor of 2 lowered the resistance by only 2% which is not significant. The resistor meander test revealed that resistor meanders that are 5μm wide do affect the final sheet resistance due to a rounding effect of the processed body of the resistor while meanders greater than or equal to 10μm spacing do not affect the resistance. The resistor

width test revealed an anomaly which causes 10% variation of the effective sheet resistance over the 5μm to 30μm resistor width range. Undercutting was observed which caused the resistor width to be widened near the contacts and affected the sheet resistance of the 5μm length resistor significantly.

The test pattern resistors and doped films were examined to study resistor linearity, contact resistance, resistor reproducibility and TCR behavior. Linearity of the SIPOS resistor structure was found to be dependent on both implant dose and on the electric field applied across the finished resistor. For implant doses of $\lesssim 10^{14}/cm^2$, the structure exhibited a bimodal conduction resembling a diode under reverse bias. For implant doses above the critical dose, SIPOS resistors are linear up to electric fields of 2KV/cm and decrease in resistance by 10% or less for electric fields up to 6KV/cm. Contact resistance was found to be dose dependent and typically varied between 0.5 and 1.0 square of sheet resistance. Preliminary measurement of the temperature coefficient of resistance on a 12% oxygen concentration film yielded 705 ppm/°C. Resistor reproducibility was found to be very sensitive to oxygen content and ion implant dose variations as well as anneal conditions. A ±3% oxygen content variation yielded a 100% sheet resistance variation. And a ±3% ion implant dose variation yielded 50% variation in the sheet resistance. Combining the results of sheet resistance, contact resistance, electric field dependence and TCR behavior, the

equivalent resistance for a given dose, oxygen content and fixed voltage would be:

$$R_{equivalent} = 2R_c + NR_{\square} - R_e + R_{TCR}$$

where

R_c = the contact resistance (Ω)

N = the number of squares ($\square$)

$R_{\square}$ = the sheet resistance ($\Omega/\square$)

R_e = the electric field dependence of resistance (Ω)

R_{TCR} = the temperature behavior of resistance (Ω).

A significant difference in sheet resistance was obtained between the four-point probe measurement and the calculation from a metalized resistor as shown in Figure 5. The difference exhibited between the two curves is caused by the subsequent heat treatments and processing which are dissimilar for the four-point probe film and the completed resistor structure. The very complex mechanism of impurity redistribution, different phase compositions, doping activation and different grain sizes of the film all contribute to the difference noted.

SIPOS and polysilicon obey similar transport phenomena in that both exhibit a critical dependency of sheet resistance on dose. Polysilicon obeys the carrier trapping model and SIPOS appears to also obey this model. Since the test structures were only tested under direct current conditions, the effects of carrier trapping

should be investigated to see if the linear resistive mode exhibits any frequency dependence.

Assuming the linear mode is not affected significantly by frequency, the implant doped SIPOS resistor should be useful in circuit applications which can tolerate 100% to 150% sheet resistance variability. Circuit applications which require high sheet resistance, high voltages per unit length and/or oxide isolation are especially suited to the doped SIPOS process. Additional measurements of the temperature coefficient of resistance would supply information on how the actual resistor structure behaves with temperature since the TCR measurements described earlier were made only on a SIPOS film and not on the completed SIPOS resistor. Thermal aging with applied bias on the resistor would provide information on the stability of the resistor under operating conditions.

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XI. BIOGRAPHY

Richard Snyder was born in Scranton, Pennsylvania on December 13, 1948, the son of Richard and Ruth Snyder. He attended Pennsylvania State University from which he graduated in 1968 with an Associate Degree in Electrical and Electronics Technology. Also he graduated with honors from Albright College in 1974 where he received a Bachelor of Science Degree in Physics. Richard has been employed by Bell Laboratories since 1968.